PERFORMANCE OF CDF CALORIMETER SIMULATION FOR TEVATRON RUN II

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The upgraded CDF II detector has collected first data during the initial operation of the Tevatron accelerator in Run II. The simulation of the CDF electromagnetic and hadronic central and upgraded plug (forward) calorimeter is based on the Gflash calorimeter parameterization package used within the GEANT based detector simulation of the Run II CDF detector. We present the results of tuning the central and plug calorimeter response to testbeam data.

1. Introduction

The CDF II detector at the Tevatron is presently taking data after having undergone major upgrades to keep up with the new operating conditions at increased luminosity and center of mass energy[1]. A fast simulation of the calorimeters response is a valuable and implicitly recommended tool at a hadron collider, if one wants to gain control on the systematic errors on any high-p_T related physics topic while accomodating the computing time limiting factor.

1.1. *CDF calorimetry for run II*

The CDF II calorimeters[2,3,4] — covering the region $|\eta| < 3.6$ — are of sampling type with separate electromagnetic and hadronic measurements as shown on Figure 1. In both sections the active elements are scintillator tiles read out by wavelength shifting fibers embedded in the scintillator. The calorimeters are segmented in η and ϕ coordinates in order to have a projective tower geometry pointing back to the nominal interaction point.

It has to be mentioned that the plug calorimeters have replaced the old gas calorimeters[5] used during the first generation detector (referred to as CDF I).

1.2. *The Gflash package*

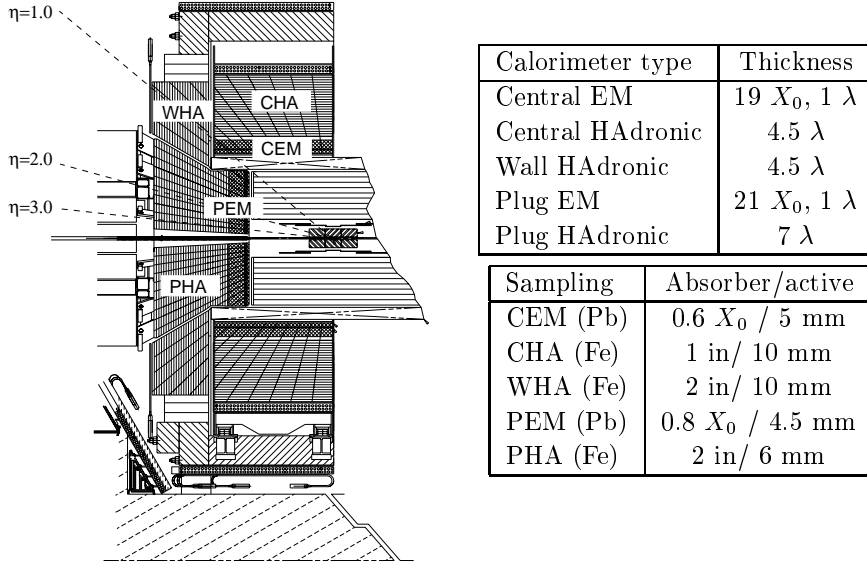Gflash is a fast calorimeter simulation using parameterized showers that is

Calorimeter type	Thickness
Central EM	19 X_0, 1 λ
Central HAdronic	4.5 λ
Wall HAdronic	4.5 λ
Plug EM	21 X_0, 1 λ
Plug HAdronic	7 λ

Sampling	Absorber/active
CEM (Pb)	0.6 X_0 / 5 mm
CHA (Fe)	1 in/ 10 mm
WHA (Fe)	2 in/ 10 mm
PEM (Pb)	0.8 X_0 / 4.5 mm
PHA (Fe)	2 in/ 6 mm

Figure 1. Elevation view of one half of the CDF II detector with depth and sampling characteristics of the various calorimeter compartments.

interfaced with the standard GEANT-based[6] simulation of the detector. The program was developed by the H1 collaboration[7] and is used as standard mass production Monte Carlo.

Electromagnetic and hadronic showers are initiated when an incident particle undergoes an inelastic interaction inside the calorimeters. New GEANT pseudo-particle and track types are defined for the showers. Gflash uses a mixture-level GEANT geometry for the calorimeters, i.e. the showers develop in a medium with effective density, Z, A, X_0 etc. It handles the energy loss of real particles inside the mixture geometry.

For the electromagnetic longitudinal profiles, a standard gamma distribution is used:

$$f(z) = \frac{x^{\alpha_i - 1} e^{-x}}{\Gamma(\alpha_i)} \tag{1}$$

where $x = \beta z$, z being the shower depth in units of X_0. The average and width of α and β parameters have a typical logarithmic energy dependence. The correlation between α and β is properly taken into account when a shower is generated:

$$\begin{pmatrix} \alpha_i \\ \beta_i \end{pmatrix} = \begin{pmatrix} \mu_\alpha \\ \mu_\beta \end{pmatrix} + \mathbf{C} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} \tag{2}$$

with matrix $\mathbf{C}$ describing the correlation between α and β determined out of GEANT results. The terms q_1 and q_2 are normal-distributed random numbers around the mean values μ_α and μ_β.

The lateral profiles are described by the following expression:

$$f(r) = \frac{2rR_0^2}{(r^2 + R_0^2)^2} \tag{3}$$

where R_0 is a free parameter that is a function of the shower energy and depth. The average profile and fluctuations of individual showers are described as (approximately log-normal) functions of the energy and shower depth. Distinction is made between the core and the increasingly slower growth of the radial extent of the shower with increasing energy.

The parameterization of the hadronic longitudinal profiles is a superposition of up to 3 gamma functions H, F, L to correctly reproduce the π^0 energy dependence:[a]

$$dE_{\mathrm{dep}} = E_{\mathrm{dep}} \left(c_h H(x)dx + c_f F(y)dy + c_\ell L(z)dz \right) \tag{4}$$

Here the α and β parameters for all the gamma distributions are allowed to fluctuate and their correlations are properly taken into account. Furthermore, to get the π^0 fluctuations right, showers are divided into 3 classes, each with a given probability.

The sampling fluctuations are reproduced by depositing a Poisson-distributed number of spots per longitudinal integration interval according to the radial probability function (3). Their energy and hence their number are given by the energy resolution that has to be reached.

These energy spots are similar to GEANT "hits" or "visible" energy depositions. In a detailed GEANT calorimeter geometry only the energy deposited in sensitive layers, as scintillators, are recorded as hits. For mixture-level GEANT calorimeter geometries, as is the case in Gflash, one needs to simulate sampling fluctuations and to explicitely convert the deposited energy E_{dep} into "visible" energy E_{vis} in the active medium

$$dE_{\mathrm{vis}}(\vec{r}) = E_{\mathrm{dep}}\hat{m} \sum_k \frac{\hat{k}}{\hat{m}} c_k f_k(\vec{r})dV, \quad k = e, had \tag{5}$$

where $\hat{m}$ denotes the sampling fraction for minimum ionizing particles (MIP), and $\frac{\hat{e}}{\hat{m}}$ and $\frac{\widehat{had}}{\hat{m}}$ are the relative sampling fractions for electrons and hadrons, respectively. The sum is over the electromagnetic ($k = e$) and the purely

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[a]Namely, H for the purely hadronic component of the shower, F for the π^0 fraction originating from the first inelastic interaction, and L for the π^0 fraction from later inelastic interactions occuring in the shower development.

hadronic ($k = had$) components, with relative fraction c_k. The azimuthally symmetric spatial distribution function is given by $f_k(\vec{r}) = \frac{1}{2\pi} f_k(z) \cdot f_k(r)$. Further details on the implementation of Gflash can be found in the original paper[7].

In the following it is shown that by tuning the same shower parameterization in Gflash it is possible to reproduce the physical response of the different sub-detectors forming the CDF II calorimetry.

1.3. *General method for tuning* Gflash

The tuning of Gflash is split according to the two sets of parameters that control on the one hand the fraction of visible energy produced in the active medium and on the other hand the energy and depth dependent spatial distribution of the various components of the shower model.

All along the tuning procedure, the consistency between data and simulation is assessed with a standard χ^2 estimator. The tuning of hadron showers proceeds as follows:

(1) The first step consists in reproducing the position and width of the MIP peak. A few parameters at a time are involved ($\hat{m}, \sigma_{\hat{m}}$ for each specific volume) as the simulation is still handled by GEANT at this stage. The width of the peaks is controlled by adjusting the amount of intrinsic and sampling fluctuations in the active medium.

(2) A sample of π^+ with an incident energy of 57 GeV is used next to set the energy scale for the peak of full energy deposition (involving $\frac{\hat{k}}{\hat{m}}$ and c_k).

(3) The energy dependence of the $f_k = f_k(E)$ parameters defining the fractions of deposited energy is tuned to accomodate the data at all energies. This step is basically iterative once a partial deconvolution of Ansatz (5) set "pivots" typically being two points with a large energy gap.

(4) The tuning of the lateral profile is performed almost independently of the tuning of the longitudinal energy dependence.

2. Tuning Gflash with testbeam data

The Gflash package is tuned using testbeam data[8] including electrons and pions with energies in the range $8 < E < 230$ GeV.

Focus will be made on the tuning of hadronic showers, as being the most involved part of the description. The tuning of the electromagnetic showers, although obviously valuable, presents less difficulty.

2.1. *The MIP peak*

The MIP peak is measured in the electromagnetic compartment with pions. Besides of the position and width of the peak, the ratio of the peak content to the total number of measured pion showers provides an additional handle on the tuning, as it can be directly inferred from the geometry of the detector (see absorbtion/interaction lengths in Figure 1).

Figure 2 shows the comparison between testbeam data and Gflash simulation for 57 GeV pions in the CEM calorimeter. The same level of agreement is reached in the plug calorimeter.

2.2. *Setting the energy scale*

The hadronic energy scale in the tuning procedure is set by the response of 57 GeV pions both in the central and plug calorimeters.

A set of reference plots shown on Figure 4 is used as a reference for adjusting the parameters steering the longitudinal development of the hadronic showers in the combined calorimeter compartments.

Plots (a)–(d) respectively show the distribution of the measured total energy (electromagnetic+hadronic) for pions that are minimum ionizing in the PEM, the measured total energy for all the pions, the hadronic fraction of the deposited energy as measured in the PHA and the electromagnetic fraction of the deposited energy as measured in the PEM. The χ^2 estimator confirms that data and simulation are in fair agreement for each distribution.

The same level of agreement is reached for hadronic showers in the central calorimeter. The purely electromagnetic showers are simultaneously well reproduced as illustrated on Figure 3. Plotted is the energy over momentum ratio for 11 GeV electrons.

2.3. *Adjusting the energy dependence*

Once the MIP distribution and the hadron energy scale are set, the other datasets can be reproduced by tuning the logarithmic dependence in energy of the shower components.

Given the significant difference between the central and plug hadronic calorimeters construction, in particular when comparing their sampling structure (see Figure 1), two distinct parameterizations of the energy dependence for the fractions of deposited energy are kept (c_h, c_f, c_ℓ in Equation (4)).

On Figure 5 (top) the mean value $\langle E/p \rangle$ of the ratio of the measured total energy over the momentum of the incident particle in the central hadronic calorimeter is plotted versus momentum. Since the scintillator-based plug
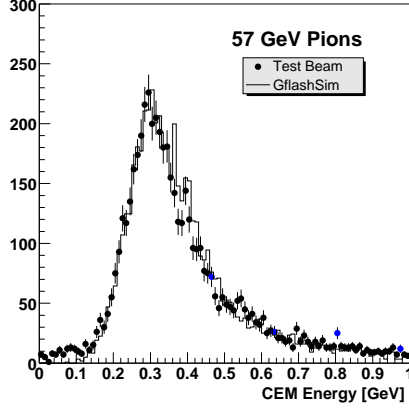
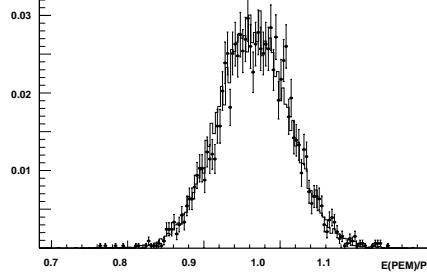Figure 2. Peak for minimum ionizing particles in the CEM for 57 GeV pions.

Figure 3. Ratio E/p =(calorimetric energy)/(beam momentum) for 11 GeV electrons in the PEM.
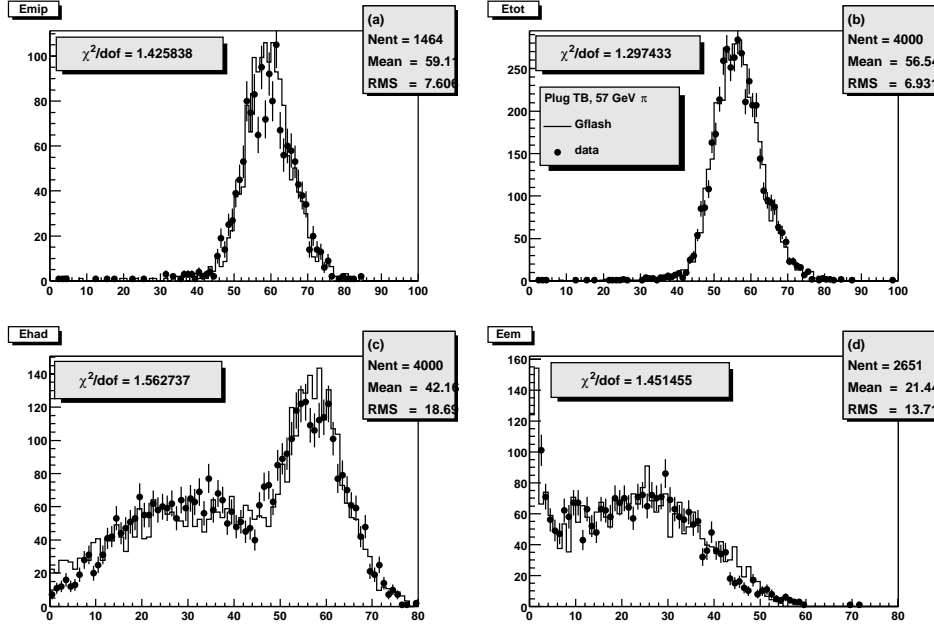

Figure 4. Comparison of the energy profiles between testbeam data and simulation using **Gflash** showers parameterization for 57 GeV pions. (a) Total energy for pions that are minimum ionizing in the PEM (see text). (b) Measured total energy for all the pions. (c) Hadronic fraction E_{had} of the deposited energy as measured in the PHA. (d) Electromagnetic fraction E_{em} of the deposited energy as measured in the PEM. Abcissas are in [GeV].
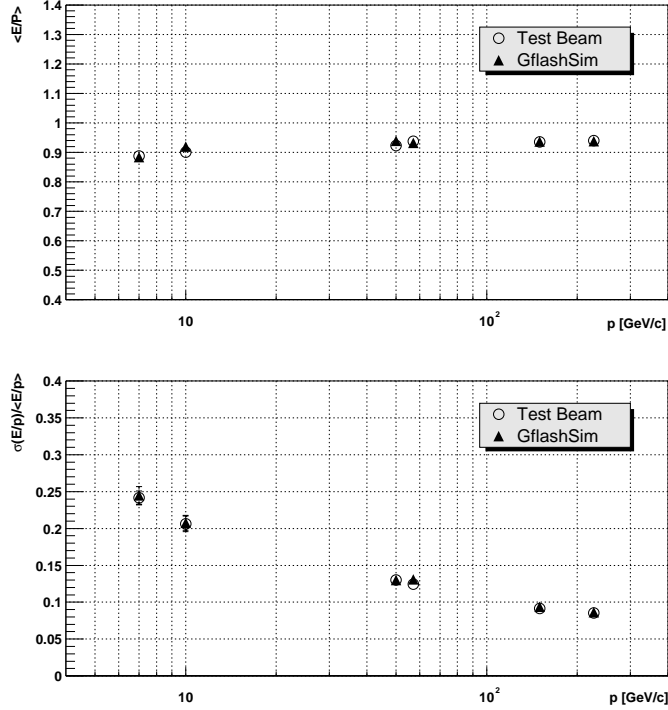
Figure 5. Comparison of the linearity in the central hadronic calorimeter (CHA) between testbeam data and Gflash simulation. *Top:* Average ratio $E/p =$(calorimetric energy)/(beam momentum) as a function of momentum. *Bottom:* Width of the E/p distribution versus momentum.

calorimeter is not compensating, the response is non-linear with the pion energy. The bottom plot shows the corresponding width $\sigma(E/p)/\langle E/p \rangle$ of the distributions. Both the peak position and the energy resolution are quite well reproduced by the current tuning of Gflash over the momentum range $8 < E < 230$ GeV. The same level of agreement is reached for electromagnetic showers over the same range of momenta.

Error bars are displayed on both plots although mostly covered by the marker size. The main contribution comes from the uncertainty on the determination of the beam line parameters.

2.4. *Lateral profile*

For the tuning of the lateral profile, the data consist of tracks obtained from minimum bias events and measured in the central part of the CDF II detector.

The available energy range spans from 0.5 GeV to 2.5 GeV. At higher energies, tuning follow-ups are performed with the increased amount of data becoming available.

The tuning of the lateral profile can mostly be done independently of the longitudinal one. The approach is typically iterative.

Figure 6 shows the comparison between the minimum bias data and the Gflash simulation. The histogram of the simulation is normalized to the data to avoid a longitudinal dependency.
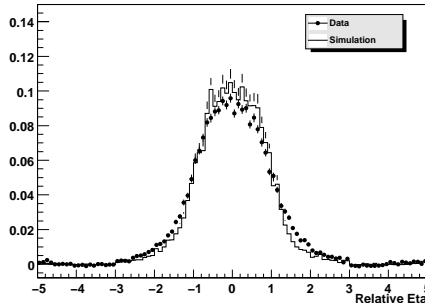

Figure 6. The tuned plots of the lateral profile for CHA using tracks from minimum bias events. The lateral profile is expressed in units of pseudo-rapidity relative to the center of the tower the incident track is pointing to.
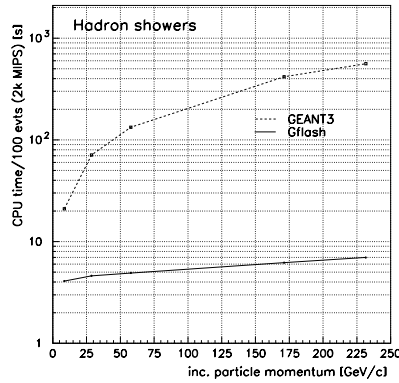

Figure 7. Comparison of CPU time consumption between GEANT and Gflash hadronic shower simulation.

3. Remarks and conclusions

The typical gain in CPU time using the Gflash parameterization with respect to the standard GEANT simulation to generate hadronic showers is up to a factor 100 as shown on Figure 7. This work allowed the integration of a fast shower parameterization based on the Gflash package in the CDF II simulation framework. The calorimeters response is reproduced in an unified description over the close to 4π coverage of the detector.

Acknowledgments

References

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